



Demonstration of PIV in a Transonic Compressor

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1. SUMMARY

Particle Imaging Velocimetry (PIV) is a powerful measurement technique which can be used as an alternative or complementary approach to Laser Doppler Velocimetry (LDV) in a wide range of research applications. PIV data are measured simultaneously at multiple points in space, which enables the investigation of the non-stationary spatial structures typically encountered in turbomachinery. Many of the same issues encountered in the application of LDV techniques to rotating machinery apply in the application of PIV. Preliminary results from the successful application of the standard 2-D PIV technique to a transonic axial compressor are presented. The lessons learned from the application of the 2-D PIV technique will serve as the basis for applying 3-component PIV techniques to turbomachinery.

2. INTRODUCTION

Recent advances are leading to the emergence of PIV as a powerful velocity measurement technique which can be used as an alternative or complementary approach to LDV in a wide range of research applications. Refined data processing techniques and continuous increases in computational power have made PIV a more widely available and practical measurement technique. Stereo viewing optical configurations provide planar 3-component velocity measurements, which further enhances the usefulness of the PIV technique in turbomachinery applications. For a general overview of the various implementations of the PIV technique see Adrian, 1986 and Grant, 1997. PIV is a planar measurement technique wherein a pulsed laser light sheet is used to illuminate a flow field seeded with tracer particles small enough to accurately follow the flow. The positions of the particles are recorded on either photographic film or digital CCD cameras at each instant the light sheet is pulsed. In high-speed flows, pulsed Nd:YAG lasers are required to provide sufficient light energy (~100mJ/pulse) in a short time interval (<10 nsec) to record an unblurred image of the particles entrained in the flow. The data processing consists of either determining the average displacement of the particles over a small interrogation region in the image or the individual particle displacements between pulses of the light sheet. Knowledge of the time interval between light sheet pulses then permits computation of the flow velocity. Different data processing schemes are

employed depending on the number of exposures per frame and the seed particle concentration (Keane and Adrian, 1993, Wernet, 1995). While each technique has some inherent benefits, the appropriate choice depends on the characteristics of the flow and recorded image constraints.

Turbomachines are used in a wide variety of engineering applications for power generation, pumping and aeropropulsion. The need to reduce acquisition and operating costs of aeropropulsion systems drives the effort to improve propulsion system performance. Improving the efficiency in turbomachines requires understanding the flow phenomena occurring within rotating machinery. Detailed investigation of flow fields within rotating machinery have been performed using Laser Doppler Velocimetry (LDV) for the last 25 years. LDV measurements are time and ensemble averaged over all of the blade passages in a rotating machine (Strazisar, 1986, O'Rourke and Artt, 1994, Skoch et al., 1997). Since the current state of the art in computational design tools deals with time averaged flow in turbomachinery blade rows (Ucer, 1994), LDV results are well suited for comparison to CFD predictions of the averaged flow fields. While a series of instantaneous spatial velocity measurements obtained using PIV can be averaged together to compute the time-mean flow field, individual PIV images enable the study of non-stationary spatial flow structures, making PIV a very powerful diagnostic for the study of unsteady flow phenomena.

Numerous researchers have employed various PIV techniques to study the unsteady flows in rotating machines. Paone et al., 1988, used PIV to make blade-to-blade plane velocity measurements in a centrifugal compressor. Although not a rotating machine application, Bryanston-Cross et al, 1992 described photographic PIV measurements obtained in a transonic turbine cascade rig. The light sheet illumination was introduced via an 8.0 mm diameter hollow turbulence generating bar which was already part of the experimental rig. Post et al., 1991 also discuss PIV measurements in a turbine cascade using photographic film. In this work color film was employed and the light sheet pulses were of two distinct wavelengths, which then permitted cross-correlation data reduction of the electronically digitized photographs. Coginini and Goss, 1997 have described a two color digital PIV

technique which should be applicable to turbomachinery applications. A high resolution (3000x2000 pixel) single CCD sensor color camera is employed to record the particle images at two instances in time on a single CCD image frame using red and green illumination pulses. Shepherd et al, 1994 used photographic PIV to study the flows inside both centrifugal and axial fans. The test setups employed water as the working fluid and hence were restricted to low rotational speeds. Tisserant and Breugelmans, 1997 used a digital PIV technique to measure the flow field in a subsonic (30-70 m/s, 3000-6000rpm) axial fan. They noted that an optical periscope type probe (similar to that used by Bryanston-Cross, et al 1992) is required for introducing the light sheet into the flow and that out-of-plane velocities are sometimes significant, causing a loss of correlation of the in-plane velocities. Rothlübbers et al, 1996, used digital PIV to study the flow in a radial pump. Low seed particle concentrations were identified as not suitable for rotating machine studies, where high spatial resolution measurements are required. Oldenburg and Pap, 1996, used a digital PIV setup to investigate the flow field in the impeller and volute of a centrifugal pump. The lab scale facility used water as the working fluid and a transparent impeller.

The application of PIV to turbomachinery at NASA Lewis Research Center (LeRC) is a two stage program wherein 2-D PIV is initially applied to resolve issues regarding optical access, light sheet delivery and flow seeding. In the second phase of the program, a stereo viewing optical system employing tilted CCD sensor planes which satisfy the Scheimpflug condition will be used to acquire planar, 3-component velocity measurements. The stereo viewing planar, 3-component PIV technique utilizing Fuzzy inference for maximized data recovery has been previously demonstrated in a supersonic nozzle flow at LeRC (Wernet, 1996).

In this work we discuss the successful application of digital PIV to a transonic compressor. Measurements have been obtained in a single stage 50.8 cm diameter transonic axial compressor facility at LeRC. The measurements were obtained using upstream illumination of the blade-to-blade rotor passage at a rotational speed of 17,150 rpm and also using downstream illumination at a rotational speed of 13,800 rpm. A special optical periscope probe was used to generate and introduce the light sheet into the flow. A brief description of the optical setup and some preliminary results are presented. Techniques for averaging together PIV velocity vector maps with spurious vectors are also presented and discussed. The averaged measurements illustrate that PIV yields high accuracy velocity vector maps in much less time than traditional LDV techniques.

3. OPTICAL ACCESS AND LIGHT SHEET DELIVERY

Obtaining optical access to the flow field is never a trivial issue in rotating machine applications since the casing through which the measurements are to be made is cylindrical. Ideally, the optical access port will permit the collection of light scattered from particulates in the flow without significantly disturbing the flow. The LeRC transonic compressor facility has a large optical access port which is curved to match the radius of curvature of the compressor casing. Backscatter LDV systems are reasonably well suited for the single optical access port typically encountered in turbomachinery applications. However, the standard PIV technique requires that the light scattered by the particles traversing the light sheet be collected at 90° from the plane of the light sheet. Hence, the light sheet must be introduced either upstream or downstream from the optical access port used for scattered light collection and directed along the flow direction. Care must be taken to insure that the light sheet optics do not disturb the stream tube feeding the blade passage under study. If the propagation direction of the light sheet is aligned with the stagger angle of the blades and the optics are located sufficiently far upstream or downstream, then the flow in the measurement region will not be disturbed.

A very compact light sheet delivery system was constructed using a periscope type configuration as shown in figure 1a. The pulsed Nd:YAG beam is directed down the bore of the tube which contains light sheet forming optics and a 90° turning mirror. The periscope probe has an outside diameter of 12.7 mm and utilizes 8 mm diameter optics (200 mm focal length spherical and -25 mm focal length cylindrical lenses) to form the Nd:YAG laser beam into a laser sheet. The light sheet exits the probe through a window which keeps the optics inside the probe protected from contamination by seed material. An implementation of this NASA designed and constructed probe is shown in operation in figure 1b. The small diameter periscope probe is inserted through the compressor casing upstream of the measurement location, see figure 1c. Moving the probe in and out through the casing changes the spanwise location of the illumination plane. In order to align the propagation direction of the light sheet along the blade stagger angle, the light sheet probe is inserted below the horizontal rig centerline. This insertion location also ensures that the light sheet probe does not disturb the flow upstream of the actual measurement location. The mounting base which attaches the probe to the casing is designed so that the light sheet generating probe is oriented horizontally, even though the entrance point through the rig casing window is below the horizontal centerline of the rig. Maintaining a horizontal entry ensures that the plane of the light sheet

will remain parallel with the axis of the compressor, simplifying the recording system requirements. Figure 1d shows a photograph of the PIV system installation in the compressor rig. Downstream illumination is being used in this configuration. The Nd:YAG laser is observed in the lower left corner of the picture along with an articulated arm which extends from the laser over to the light sheet probe. The light sheet illumination can be seen in the compressor blade rows and the PIV camera is mounted next to the rig.

In the periscope probe configuration, directing the pulsed laser beam down the bore of the periscope tube is extremely challenging. An articulated light arm with mirror joints was used to easily and reliably direct the beam down the bore of the probe, see figure 1c and d. Articulated light arms for Nd:YAG laser beam delivery are commercially available from several commercial PIV vendors and permit the full energy range of the laser to be used (200 mJ/pulse at 532 nm). Use of the light arm simplifies the coupling of the Nd:YAG beam to the periscope and also adds an increased level of safety to the installation since the beam is entirely enclosed when outside of the compressor casing. The light sheet delivery probe depicted in figure 1a has been successfully used by the author to deliver 125 mJ pulsed illumination into the compressor facility.

4. SEEDING

A uniform and sufficiently high concentration of flow seeding is the most critical element in any PIV experiment. If the number of particles recorded on the CCD image frame is too low, then correlation techniques cannot be applied, although particle tracking could still be utilized. As discussed previously, particle tracking does not typically provide a sufficient density of measurements necessary to adequately characterize the complex flows encountered in turbomachinery (Rothlübbers et al, 1996). However, provided the particle concentration is sufficiently high to support correlation computations particle tracking can be combined with the correlation technique results to provide high spatial resolution velocity estimates (Keane and Adrian, 1993, Wernet, 1995).

The global facility seeding system developed for use in laser anemometry measurement programs in the transonic compressor facility was inadequate for PIV measurements. A sample calculation reveals the inadequacy. An LDV experiment utilizing a probe volume that is 100 μm in diameter by 500 μm long to measure a 200 m/s flow may achieve a data rate of 2KHz. This measurement rate is obtained by using a seed particle concentration of 0.2 particles/ mm^3 . Conversely, in a digital PIV experiment where the field of view is 50x50 mm (yielding a spatial resolution of

about 50 $\mu\text{m}/\text{pixel}$), the light sheet thickness is 1 mm, and the interrogation region size is 32x32 pixels, the required seed particle concentration to ensure that there are 15 particles per interrogation region (or 15 particle pairs for double exposure image capture) is 6 particles/ mm^3 . Hence, the seeding requirements for PIV are more than an order of magnitude higher than that required for LDV.

Global seeding of a large scale facility with high mass flow rates for PIV measurements is impractical. Instead, the seed material must be introduced locally near the measurement plane. For transonic flows, sub-micron particles are required for accurately following the flow. A multiple jet atomizing seeding system employing smoke juice and producing particles with a nominal diameter of 0.7 μm seeds the flow field via a small diameter tube through the compressor casing. Locating the seed injection tube many tube diameters (> 70) upstream of the measurement station provided sufficient seed particle concentrations for correlation processing of the collected PIV images while adding negligible disturbance to the measurement region.

5. IMAGE ACQUISITION AND PROCESSING

The primary factors influencing the choice of image acquisition and processing techniques for the LeRC turbomachinery application are: efficiency of rig run time; maximum flexibility in image manipulation and storage; and optimal data processing. Although photographic film offers the highest spatial resolution image measurements, electronic image acquisition has several advantages such as: enabling cross-correlation processing; real time feedback of the flow seeding conditions; optimization of the laser inter-pulse timing; image focusing; on-line assessment of flare light from blade surfaces and simplified data archiving and storage (image files instead of photographic film). A judicious choice of the camera field of view can result in acceptable levels of spatial resolution. CCD cameras with 1000x1000 pixel sensors can image a 50x50 mm field of view with 50 $\mu\text{m}/\text{pixel}$ resolution. Assuming 64x64 pixel processing subregions with 50% overlap, the resulting velocity vector grid will have approximately 1.6 mm spatial resolution. In cases where larger fields of view are required and/or high resolution CCD imagers are not available, photographic film may be the only acceptable choice.

Another advantage to using electronic image capture in PIV image acquisition has to do with correction of the images from window distortions. In many cases the optical access ports used to record the PIV image data are curved to match the inside diameter of the turbomachine casing. Image capture through these curved windows results in image distortion. By

recording a reference image of a calibration target with a Cartesian grid of points, a set of image warping coefficients can be computed to correct for the effects of the window distortion. The image warping is readily applied to the digital imagery, but is not so straightforward when photographic recording is used.

Submicron particles are required to faithfully follow the flow in transonic machinery. Although the spatial resolution of the optical system is much larger than the actual geometric image of the particle on the CCD sensor, the diffraction effects of the optical system may produce effective particle images which are much larger (Adrian, 1986). For example, using an $f/30$ optical recording system operating at a magnification of 0.16 and illumination wavelength of $0.532\text{ }\mu\text{m}$, would yield $45\text{ }\mu\text{m}$ diameter diffracted particle images for $0.7\text{ }\mu\text{m}$ particles. The diffracted particle images are on the order of the pixel size and hence will result in a minimal correlation peak centroid estimation error, (Wernet and Pline, 1993)

Cross-correlation data reduction is the optimal data reduction technique for PIV since it offers directionally resolved velocity vectors, no self correlation peak and hence no restriction on the minimum particle displacement between exposures (the relative accuracy of the velocity measurements is inversely proportional to the displacement between exposures, therefore a reasonable displacement is desirable). To facilitate cross-correlation data processing, a pair of single exposure image frames are required. Refinement of the "frame-straddling" technique first demonstrated by Wernet, 1991 has led to the development of commercial PIV cameras which permit a pair of image frames to be acquired with a very small inter-frame period ($<1\text{ }\mu\text{sec}$). The cameras employed are standard RS-170, 60 fields/sec video cameras or high resolution full frame CCD imagers running at 30 frames/sec. Using the frame-straddling technique, both camera systems offer inter-frame exposure intervals of $1/30\text{ sec}$ down to $<1\text{ }\mu\text{sec}$.

Flare light reaching the CCD camera can cause significant amounts of blooming, leaving large areas of the imaged field useless. Aligning the light sheet along the blade stagger angle minimizes the intersection area of the light sheet with the blade surface, hence, significantly reducing the amount of surface flare light. Painting the rotor hub and blades black also significantly improves the signal to noise ratio in the recorded images. Some flare light from the blade surfaces is desirable for referencing since it marks the position of the blade leading edge/surface in the recorded images. When all else fails, black tape can be placed on the optical access port window to block flare light caused by the light sheet hitting the blade surfaces.

Recently available commercial PIV systems provide user friendly software interfaces and have made the technique close to "turn key". The main benefit of these commercial PIV systems stems from their ability to provide real-time, or very nearly real-time velocity vector maps from the acquired imagery by using electronic cameras and fast data processing. The electronic image acquisition and real-time processing of the acquired imagery provides immediate feedback to the experimenter on the quality and uniformity of the flow seeding, the appropriateness of the selected inter-pulse exposure interval and laser power level. Once the experimental parameters have been fine-tuned the data acquisition system can be configured to rapidly acquire a series of data sets so that average flow properties can be computed.

For the acquisition of images from facilities with high overhead costs, PIV systems which allow fast acquisition and storing of the acquired digital images are most desirable. Fast processing of the data is not important once the experimental parameters have been optimized; however, archiving the original image data is extremely important. The processing parameters selected during the initial setup may not prove to be the best settings for achieving the maximum information recovery from the raw PIV images. Archiving all of the raw image data permits the investigation of spurious results in the processed vector fields. Without the raw image files there is no way to discern the real cause of spurious vectors. Additional image processing steps may be required to maximize information recovery in regions of the image where noise levels are high, or particle concentrations are low. The application of combined correlation/particle tracking data processing strategies are usually performed off-line due to the longer processing times and steps involved. Finally, future improvements in data processing algorithms and techniques may permit better data extraction. For all of these reasons, storing the original image files is desirable and may save the expense of having to rerun the experimental tests.

6. AVERAGING VELOCITY VECTOR MAPS

Each PIV measurement realization is spatially averaged and the accuracy of the average particle displacement estimate across the interrogation region depends on several factors: the particle seed density in the fluid must be high enough so that on the order of 15 particles are recorded in each interrogation region; the tracer particles must be sufficiently small so that the particles accurately follow the flow; and the recorded particle images should be small in order to minimize the error in estimating the particle displacement peak (Wernet and Pline, 1993). When these criteria are satisfied, PIV estimates on the order of a few percent are obtained

(Adrian, 1986). Averaging the results from several hundred image frames will lower these errors, yielding accuracies which are comparable to those obtainable with LDV, and yet the total acquisition time for the PIV data is nearly an order of magnitude shorter.

One of the advantages of PIV over traditional point averaging techniques such as LDV is that both the instantaneous and average flow field properties can be examined. The sequence of instantaneous PIV images that are acquired must be combined to compute the average flow field quantities. This would be a straight forward process if all of the PIV images were uniformly seeded and of good quality. However, while the seed density is generally reasonably uniform, some image frames are acquired with sparse or non-uniform seeding. When processed, these images will yield velocity vector maps which are incomplete or have spurious vectors where the seed density is inadequate for proper correlation processing. These spurious vectors will have a detrimental effect on the computed mean flow properties, and therefore a procedure for judiciously removing them must be used.

The procedure devised for computing the mean flow quantities from a series of processed PIV image velocity vector maps utilizes both hard velocity cutoff limits and an automated procedure for identifying outliers. The high and low velocity cutoff limits set by the user are applied and then the mean and standard deviation are computed at each grid point in the velocity vector map. The automated procedure for removing outliers is based on Chauvenet's criterion, (Taylor, 1982) in which the probability of occurrence of a given point deviating from the mean is computed. The main assumption here is that the parent velocity distribution is Gaussian. The number of standard deviations that a given point lies from the mean is first computed. Then the probability that a given point should deviate from the mean by this many standard deviations is computed from the error integral and multiplied by the number of points in the distribution. If the computed probability is less than a preset level then the point is removed. This technique may not be appropriate in instances where the parent distribution is not Gaussian, such as in the vicinity of a shock where the distribution of velocity measurements may be bimodal. An advantage of this technique is that it relies on the computed mean flow properties over several independent image frames to discriminate spurious vectors. In a single instantaneous PIV image acquisition, other criteria such as the ratio of the correlation peak to the first noise peak must be used, which can mistakenly remove good data points from the image maps. Other techniques for validation of the instantaneous velocity vector maps exist (Wernet, 1995), however, none of these techniques were used to process the measurements presented here.

7. EXPERIMENT

The facility used in the study is a 50.8 cm diameter, single stage axial compressor with a design speed of 17,188 rpm and a mass flow rate of 20.19 kg/s. The rotor has 36 blades with a span of 75 mm at the leading edge and 56 mm at the trailing edge. The blade stagger angle is 41° at the hub and 61° at the tip. The casing is fitted with a large optical access window (200×100 mm) which is molded to the complex contour of the casing. The glass thickness is 3 mm and produces a very small amount of optical distortion. None of the optical distortion effects will be considered here.

The seeding was provided by a 6 jet atomizer (producing $0.7\ \mu\text{m}$ diameter particles using Rosco's smoke juice) which injected seed through a 6 mm diameter seeding probe located approximately 80 probe diameters upstream of the rotor. The seeding probe position could be adjusted radially to provide seed in the plane of illumination. The light sheet was introduced into the rig via a LeRC-designed and built optical periscope probe depicted in figure 1a. The probe was inserted through the casing at two locations: at a circumferential position 45° below the rig centerline and approximately 200 mm upstream of the rotor; and also at 45° above the rig centerline and 240 mm downstream of the rotor. The inclination angle of the light sheet roughly matched the blade stagger angle at both mid span for the upstream illumination case and near the blade tip for the downstream illumination setup. The light sheet generated by the probe was approximately 45 mm wide and 1 mm thick at the measurement location. A commercial articulated light arm was used to couple the light from a dual cavity Nd:YAG laser system to the periscope probe. The Nd:YAG light sheet pulse energy was approximately 125 mJ/pulse. A schematic representation of the optical system implementation in the compressor rig is depicted in figure 1c.

Commercial PIV system software running on a PC was used to collect and analyze the data. No array processing hardware was required. A 1000×1000 pixel cross-correlation CCD camera utilizing frame-straddling was used to acquire pairs of single exposure images. An adjustable electronic delay triggered from a once-per-rev signal on the rotor was used to trigger image acquisition and laser firing to record PIV data from a selected blade passage on the rotor wheel. The camera image acquisition and laser firing were all software controlled via a commercial synchronizer. Correlation processing was used to initially verify that sufficient seed particles were present and that the appropriate laser inter-pulse timing had been selected. After the PIV experimental parameters were determined, raw PIV images were acquired directly into the PC's memory and then saved directly to disk without processing the images. Correlation processing of the images was performed off-

line after the experiment was completed. The image acquisition rate was 10 frame pairs/sec (limited by the Nd:YAG laser repetition rate) and the time to store each image to disk was approximately 1 second. This data acquisition mode minimized the rig run time and offered maximum flexibility in the selection of the appropriate post processing of the acquired images.

8. RESULTS AND DISCUSSION

For the upstream illumination case the camera image scale factor was $56 \mu\text{m}/\text{pixel}$, yielding a $56 \times 56 \text{ mm}$ field of view, and the inter-frame time was $2.67 \mu\text{s}$. The light sheet illumination covered most of a blade passage in the circumferential direction at a passage height of 46 mm from the hub (70% span). The plane of the light sheet intersected the lower blade at constant radius, but was slightly inclined along the pressure surface of the upper blade. The compressor was operated at 17,150 rpm and a mass flow rate of 20.14 kg/s, yielding a pressure ratio of 1.86. The flow velocity upstream of the rotor is 190 m/s and the blade speed at the measurement plane is 390 m/s. The flow direction is from left to right and the rotational direction is from top to bottom. A single exposure raw PIV image is shown in figure 2a and a processed instantaneous velocity vector map in figure 2b. Figure 2a shows the relative positions of the blades and the level of particulate seeding. Tape has been placed on the windows to reduce the flare light scattered off of the blade surfaces. The blade profiles at the measurement plane location are shown in figures 2b-d. The vectors in figure 2b are shown in the relative frame (wheel speed has been added) and are scaled in proportion to velocity vector magnitude and also color coded by vector magnitude. The correlation subregion size was 64×64 pixels ($3.6 \times 3.6 \text{ mm}$ subregions) with 50% overlap. Spurious vectors located around the blade surfaces and in the periphery of the image have been removed. No interpolation or data filling has been applied. Figure 2c shows the average velocity vector map from a 110 frame average of processed velocity vector maps. Under these rig operating conditions a strong shock forms off the upper blade leading edge and spans the blade passage. The position of the blade-to-blade plane shock is readily observed by the sharp drop in vector magnitude within the blade passage (pink to blue shading). A bow wave also forms off of each blade extending outward (up and to the left) from each blade leading edge. The bow wave from both the lower and upper blades are observed in the left portion of the image. There is also a significant change in velocity magnitude across the bow waves as indicated by the color shading (yellow vectors). The average velocity vector map in figure 2c is smoother and has more filled in areas than the instantaneous vector map shown in figure 2b. Figure 2d shows the relative standard deviation for the frame averaged data shown in figure

2c. The magnitudes of the relative standard deviations for each velocity vector in the average vector map are denoted by colored dots. The relative standard deviations shown in figure 2d are on the order of 5% for most of the measurements. Larger standard deviations are observed where shocks exist in the flow due to the large velocity gradients in these regions.

The computed relative standard deviations contain the effects of flow turbulence, the measurement errors of the PIV technique, the errors in the once-per-rev trigger signal and any particle seeding variations or particle lag effects. Since the expected flow turbulence is on the order of 2-3%, the low relative standard deviations shown here are believed to result mostly from the flow turbulence. The expected measurement errors from the PIV technique were previously discussed and are believed on the order of a few percent for the instantaneous PIV images, and on the order of 1% for the 110 frame average shown here. The contribution to the measured relative standard deviations arising from errors in the once-per-rev signal timing are expected to be less than 1%. The remaining particle lag errors arising from non-uniform particle seeding are also assumed to be less than 1%. Accounting for the contribution of all of these error sources agrees with the observed relative standard deviations.

Previous LDV measurements (Strazisar, 1997) acquired in the same facility under similar conditions will be used to assess the quality and accuracy of the averaged PIV data. The vertical line inside the blade profiles in figure 2c indicates the 20% chord position along the blade at 70% span. Figure 3a and 3b show the relative Mach number versus % pitch measurements obtained using PIV and LDV, respectively. The LDV measurements were obtained at a higher sampling density across the blade pitch (200 points) and are closer to the blade surfaces than the PIV measurements (17 points). Both systems show the blade-to-blade shock occurring at approximately 65% pitch. Both sets of measurements show the shock spanning about 15% of pitch. Figures 3c and 3d show the absolute flow angle versus % pitch measurements obtained using PIV and LDV. Again the measurements between the two techniques are in very good agreement, spanning essentially the same range and exhibiting similar features.

For the downstream illumination case the camera image scale factor was $53 \mu\text{m}/\text{pixel}$, yielding roughly a $53 \times 53 \text{ mm}$ field of view. The light sheet illumination covered most of a blade passage in the circumferential direction at a passage height of 50 mm from the hub at the blade trailing edge and 70 mm from the hub at the blade leading edge (nominally 91% span). Figures 4a and b show the velocity vector maps and relative standard deviations from both a 40 frame and 50 frame average of processed PIV images. The inter-frame acquisition

times were 2.67 μ s and 1.53 μ s, respectively. The correlation subregion size was again 64x64 pixels with 50% overlap. For these measurements the compressor was operated at 13,800 rpm and a mass flow rate of 15.4 kg/s, yielding a pressure ratio of 1.58. The blade speed at the measurement plane is 345 m/s. The vector magnitudes in figure 4a and b are again coded by length and color and the standard deviations in figures 4c and d are coded by color. The location and existence of the blade wake is easily identified by the low velocity region aligned with the blade. The width of the wake appears to be approximately 5 vectors across, which corresponds to a physical width of 8 mm. The location of the blade wakes in the instantaneous images were wider and randomly meandered about. Again as in the upstream rotor illumination case, the relative standard deviations are generally on the order of 5% throughout most of the image, becoming larger mainly in the blade wake region.

There are some slight differences in the velocity vector magnitudes shown in figures 4a and b. The location of the blade wake and velocity magnitude within the blade wake are essentially identical. However, the velocity vectors above and below the blade wake are of differing magnitudes and do not exhibit the same uniformity. This lack of uniformity may stem from: the unequal number of frames averaged together in the two cases; insufficient number of frames averaged in both instances; or a significant out-of-plane velocity component. The uniformity and similarity of the relative standard deviations obtained in figures 4c and d suggest that the differences in the velocity vector maps is not caused by a lack of a sufficient number of frames used to compute the averages. The upstream measurement results show that the PIV data are of high quality and have low measurement error. For these downstream illumination images there may be significant tip clearance flow near the blade tips, which manifests itself as an out-of-plane or radial velocity component. The data in figure 4b was obtained using a shorter inter-frame time and hence, should be less sensitive to the radial velocity component. The measurements in figure 4a may be biased to higher velocities since the out-of-plane velocity component may cause a loss of correlation or velocity bias due to the longer inter-frame acquisition time. No definite conclusions can be drawn from these images, however, they do emphasize the importance of measuring all three velocity components in the complex flows encountered in turbomachinery in order to unambiguously characterize the flow.

9. SUMMARY

Recent advances are leading to the emergence of Particle Imaging Velocimetry as a powerful velocity

measurement technique which can be used as an alternative or complementary approach to LDV in a wide range of research applications. Commercial PIV processors have matured to the point where they have simplified the data acquisition and reduction of PIV imagery to a "turn key" operation. Successful PIV measurements have been obtained in a transonic compressor yielding both instantaneous snapshots and time averaged velocity vector maps of the complex turbomachinery flow. Techniques were demonstrated for averaging velocity vector maps which contain spurious vectors resulting from varying amounts of particulate seeding in the captured images. The preliminary results shown here and compared with previous LDV measurements prove that the PIV technique yields fast and accurate velocity information. The average velocity vector maps obtained here in just a matter of minutes have previously taken a factor of 6 longer to obtain via LDV in similar facilities. The PIV results show clear evidence of the blade wakes. The instantaneous vector maps show the meandering nature of the blade wakes while the averaged images show the spatial extent of the disturbance. The PIV measurement errors have been shown to be less than variations caused by the flow turbulence. The nominal relative standard deviation in the PIV measurements were shown to be roughly 5%, except near shocks or in the blade wake regions.

The study of the complex flow fields encountered in turbomachinery necessitates the use of 3-component velocity measurements to fully resolve the flow field features. On the road to development of a 3-component measurement capability we have demonstrated a 2-D PIV measurement program in a transonic compressor. Future work will concentrate on extending the 2-D PIV technique to obtain planar 3-component velocity measurements in high-speed turbomachinery using a two camera, stereo viewing arrangement.

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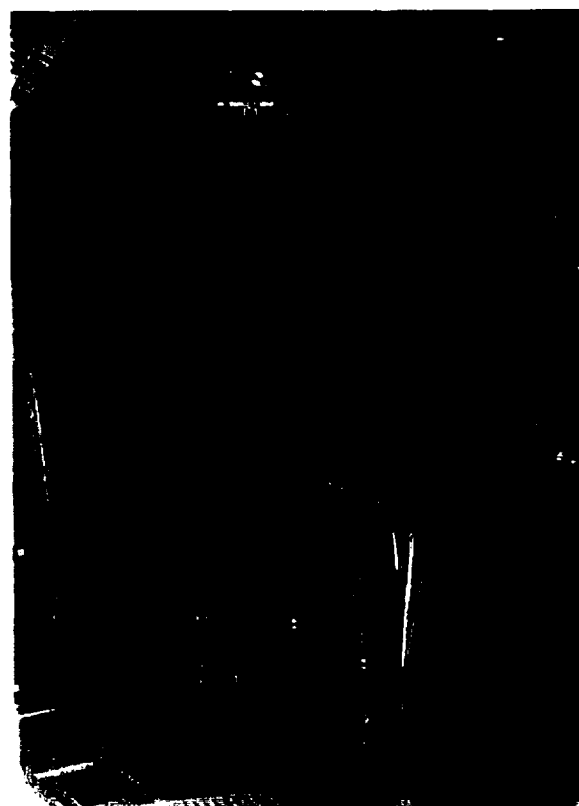
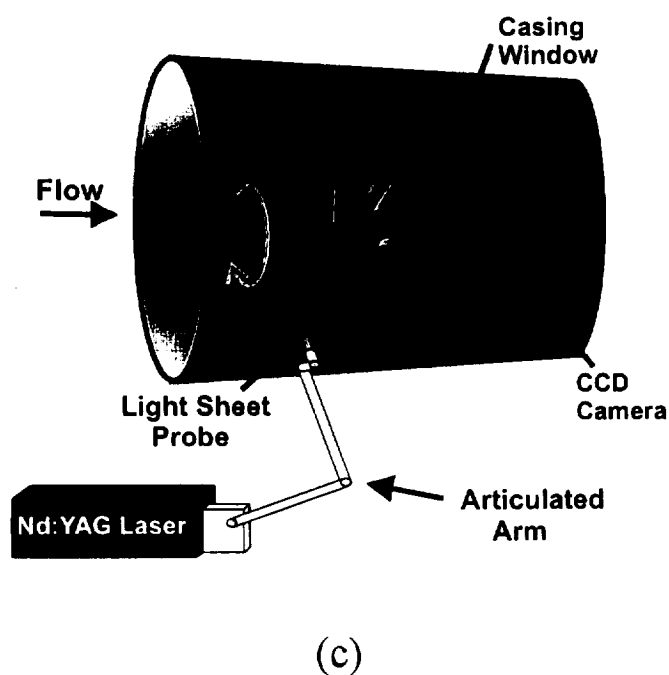
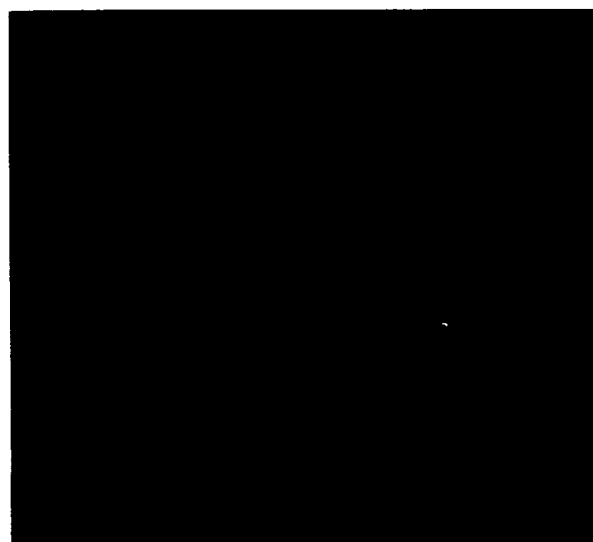
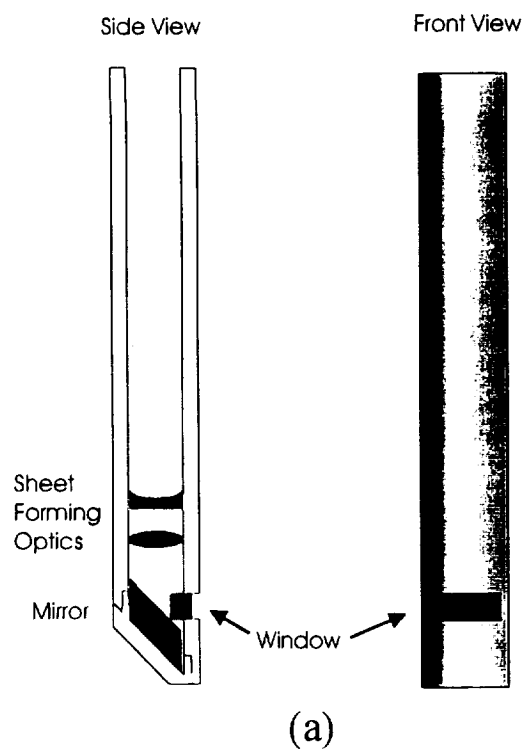
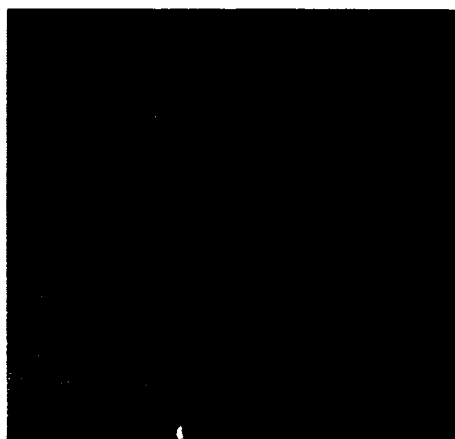
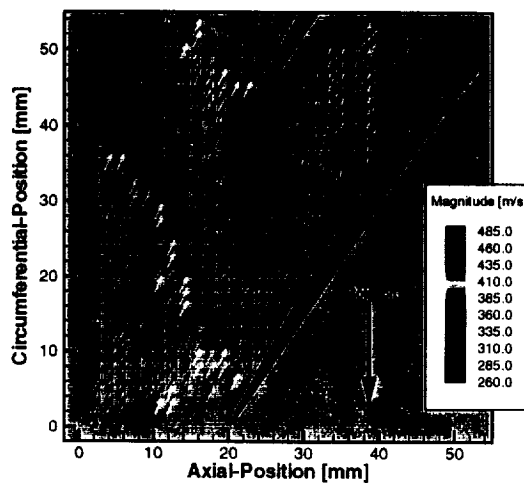


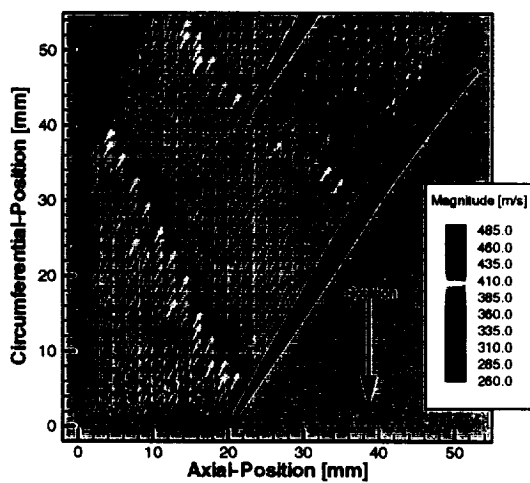
Figure 1: a) Cut away view of the light sheet periscope probe showing lenses, mirror and exit window; b) Picture of light sheet probe in operation where the light sheet emerges from the probe horizontally; c) Diagram indicating light sheet insertion into compressor rig, location of casing window and CCD camera; d) PIV system installation, note laser in lower left corner and articulated arm connecting to probe (upper right).



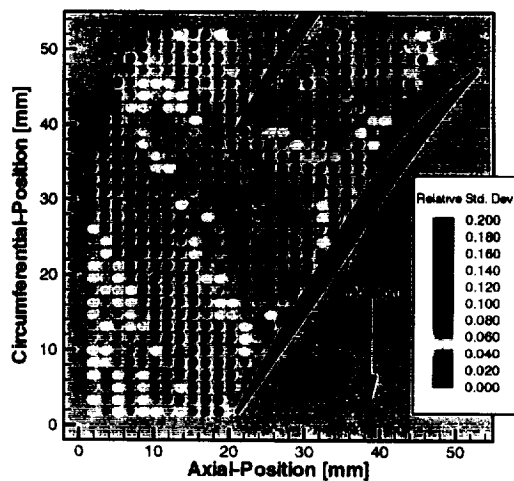
(a)



(b)



(c)



(d)

Figure 2: a) Raw single exposure CCD camera image of seed particles in compressor flow, tape has been placed on the casing window over the blades to block surface flare light; b) Instantaneous PIV image of the particle field shown in (a); c) Average of 110 processed vector maps; d) Relative standard deviation of the 110 frame average shown in (c).

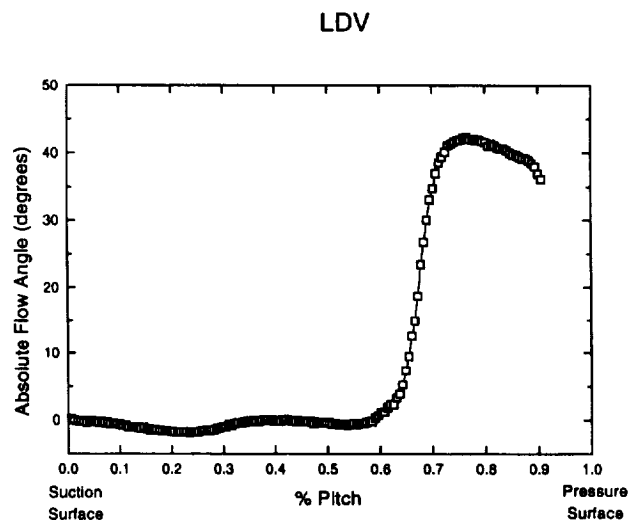
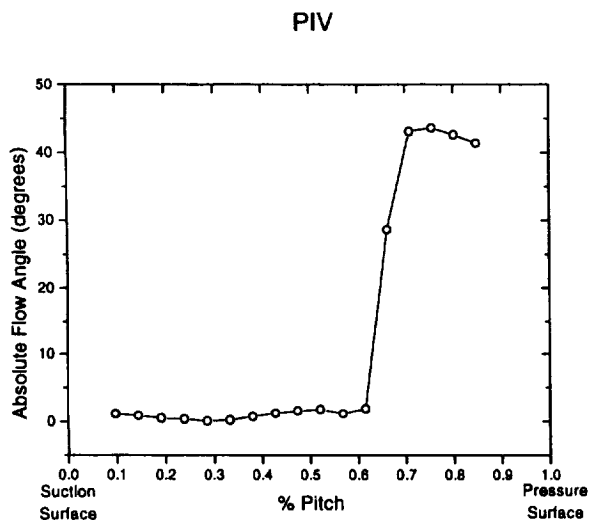
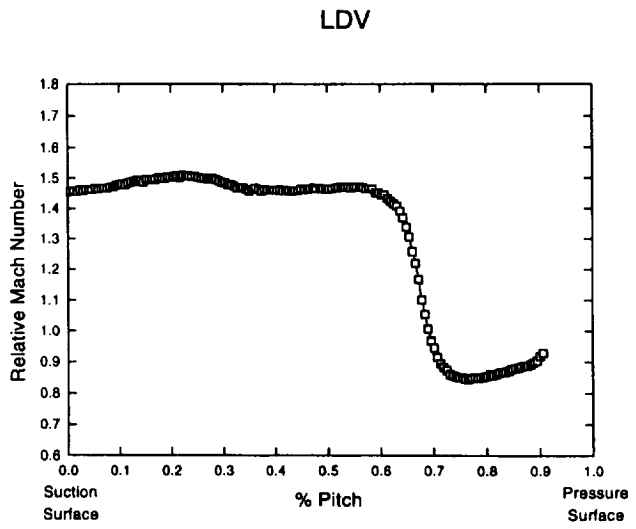
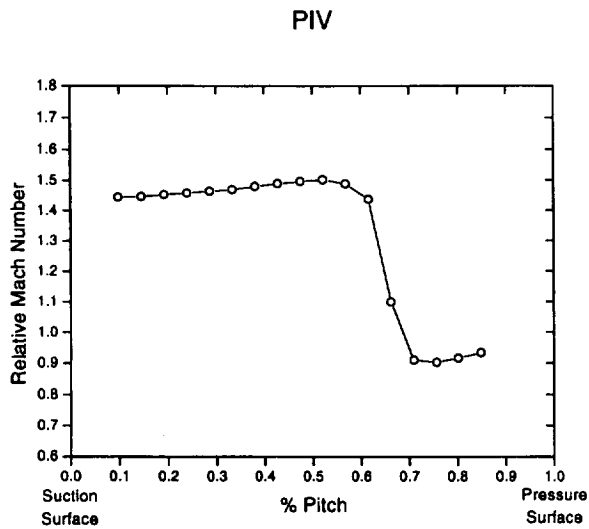
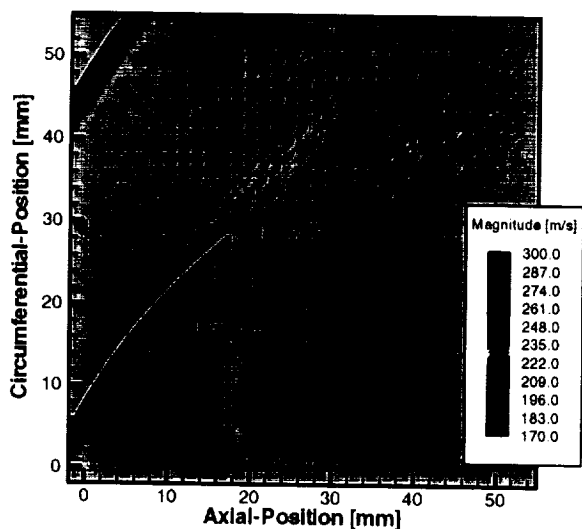
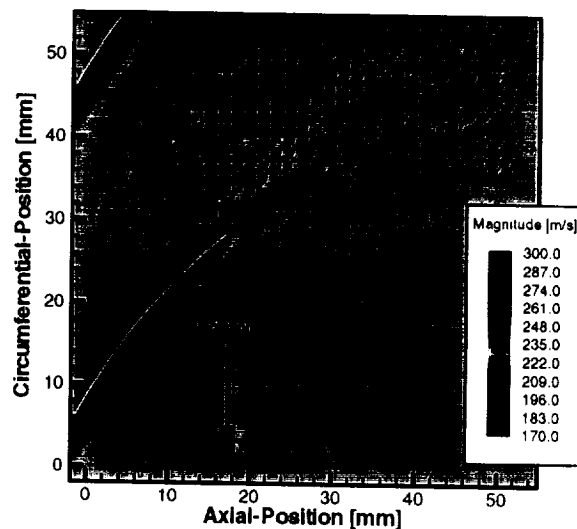


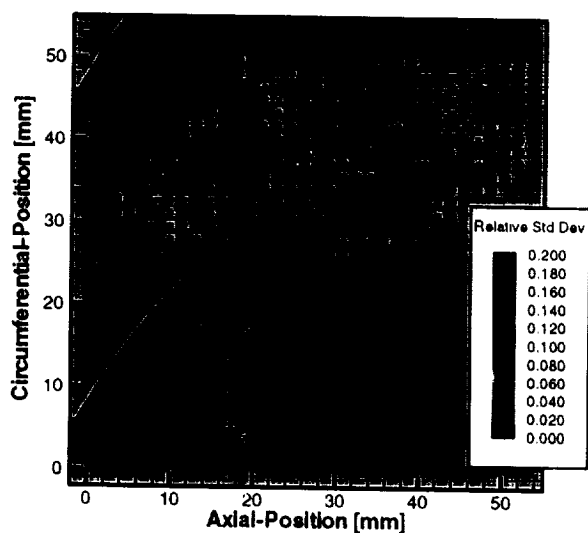
Figure 3: Comparison of PIV and LDV measurements at 20% chord for the velocity vector maps shown in figure 2. Mach number versus % Pitch for PIV (a) and LDV (b); Flow angle versus % Pitch for PIV (c) and LDV (d).



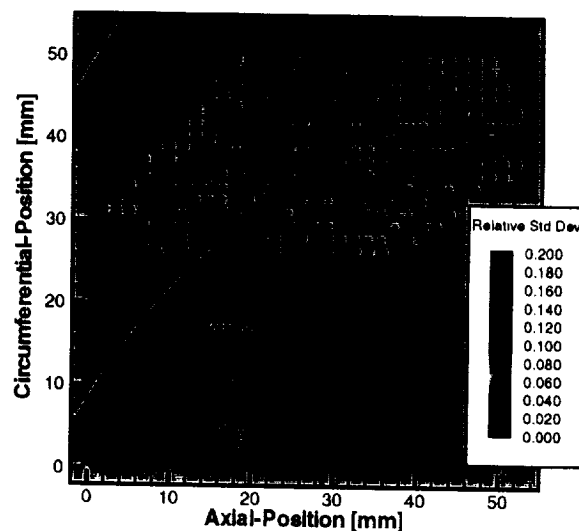
(a)



(b)



(c)



(d)

Figure 4a: Downstream illumination showing blade wakes from the average of 40 images and inter-frame time of 2.6 μ s, b) same conditions as in 4a, except 50 images have been averaged and the inter-frame time is 1.53 μ s; c&d) relative standard deviations for the velocity vector plot shown in figure 4a & b.

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